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Improving proposals for design standards of vertical cylindrical steel tanks for oil and oil products storage

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The calculation of subsidence points along the contour and in the center of the tank bottom is complicated in the case of erosion on inhomogeneous, subsidence, damaged soils, mules, flooded and seismically dangerous areas. The article analyzes the most dangerous geological phenomena, processes and complicated geotechnical conditions for the territory of Ukraine. The method of an artificial base arrangement with improved properties due to vertical reinforcement by soil cement elements is considered. Techno-economic comparison of the proposed variant with the usual pile variant of foundations (subsidence soils, estimated seismic intensity of 9 points) has been carried out. Probabilistic analysis of the artificial base has been carried out and the corellation between the probability of its failure from the percentage of reinforcement has been determined.

Keywords: complex geotechnical conditions, seismic and dynamic effects, seismic resistance, oil storage tank, artificial base, soil-cement elements, probabilistic design, stressed-deformed state, finite elements method, random variables

Пропозиції щодо вдосконалення норм проектування резервуарів вертикальних циліндричних сталевих для нафти і нафтопродуктів

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Визначено, що проектування резервуарів вертикальних сталевих (РВС) для нафти і нафтопродуктів на території України регламентується ДСТУ Б В.2.6-183:2011, який за своєю суттю замінив ВБН В.2.2-58.2-94. З'ясовано, що цей нормативний документ дає загальні рекомендації щодо вибору конструктивних рішень, навантажень і впливів при проектуванні резервуарів різного об'єму, але не враховує досягнення сучасних досліджень розрахунку напружено-деформованого стану (НДС) системи «основа – фундаменти – резервуар» у складних інженерно-геологічних умовах, особливо при динамічних і сейсмічних впливах, а також при влаштуванні штучних основ. Визначено, що головною специфікою цих розрахунків є той факт, що при проектуванні резервуарів один із основних факторів – це правильне визначення переміщень (осідань) точок по контуру та по центру його днища; такий розрахунок ускладнюється при зведенні резервуарів на неоднорідних, просадочних, заторфованих, насипних і намивних ґрунтах, мулах, підтоплених та сейсмічно небезпечних територіях. Проаналізовано найбільш характерні для території України небезпечні геологічні явища і процеси та складні інженерно-геологічні умови. Розглянуто методику влаштування штучної основи з поліпшеними властивостями за рахунок вертикального армування ґрунтоцементними елементами за бурозмішувальною технологією. Проведено техніко-економічне порівняння запропонованого варіанта зі звичайним пальовим варіантом фундаментів при будівництві резервуару на просадочних ґрунтах і при розрахунковій сейсмічній інтенсивності в 9 балів. Значну увагу приділено ймовірнісному аналізу штучної основи й визначено взаємозв'язок імовірності відмови від процента армування ґрунтової основи.

Ключові слова: складні інженерно-геологічні умови, сейсмічні та динамічні впливи, сейсмостійкість, нафтовий резервуар, штучна основа, ґрунтоцементні елементи, імовірнісний розрахунок, напружено-деформований стан, метод скінченних елементів, випадкові величини

Introduction. Steel tanks of various capacities intended for collection and storage of oil are important elements in the technological process of its extraction, preparation and transportation. In addition, they are used for pre-dehydrating oil on production field or as buffer tanks in oil trunk transport, or at petrol stations for collecting, storing and distributing various petroleum products.

Reservoirs often are built in territories with complex geotechnical conditions [1]: 1) soils with special properties (subsidence and peat (water-saturated), mule, bulk and alluvial massifs, soils which, under certain conditions, their volume increase, etc.); 2) the possibility of dangerous geological (gravitational) processes development (karst, landslides, erosion, suphosion, abrasive processes, etc.), as well as of non-uniform deformations of soil foundations during water saturation, mining operations, etc. Distribution of the main dangerous engineering geological and geological factors and processes that complicate tanks for oil and petroleum products construction and operation, on the territory of Ukraine is shown in Fig. 1 – 5 (according to the State Service of Geology and Subsoil of Ukraine and according to seismological studies [2, 3]).

The accidents with tanks for oil and petroleum products are followed by the outflow of huge masses of liquid that leads to catastrophic consequences and pollution, large-scale fires, violation of normal modes of operation the objects of transportation and storage of oil and oil products, and to significant environmental pollution and serious economic consequences also.

The main causes of accidents can be [4]: a) defects of welded joints; b) distortion of the shell shape because of its installation low quality or poor-quality of the foundation; c) the effect of low ambient air temperature; d) vibrational effects of pumps when pumping liquid; e) non-uniform subsidence of the base; f) local subsidence of the base; g) erosion of the base layer with a liquid in the case of bottom corrosion damage; h) emergency (including seismic) effects.

The degree of object damage during the earthquake depends not only on the level of seismic influences, but also on the quality of seismic design and construction. According to recent seismological studies [3], it has been established that in the territory of Ukraine, including its platform part, there is a danger of local and strong earthquakes with magnitude greater than 5 (more than 6 points on the MSK-64 scale). It creates an additional risk of existing and new oil tanks exploitation.

Figure 1 – Distribution of landslides within the administrative regions of Ukraine
(according to the State Service of Geology and Subsoil of Ukraine, http://www.geo.gov.ua)

Figure 2 – Distribution of flooding within the administrative regions of Ukraine
(according to the State Service of Geology and Subsoil of Ukraine, http://www.geo.gov.ua)

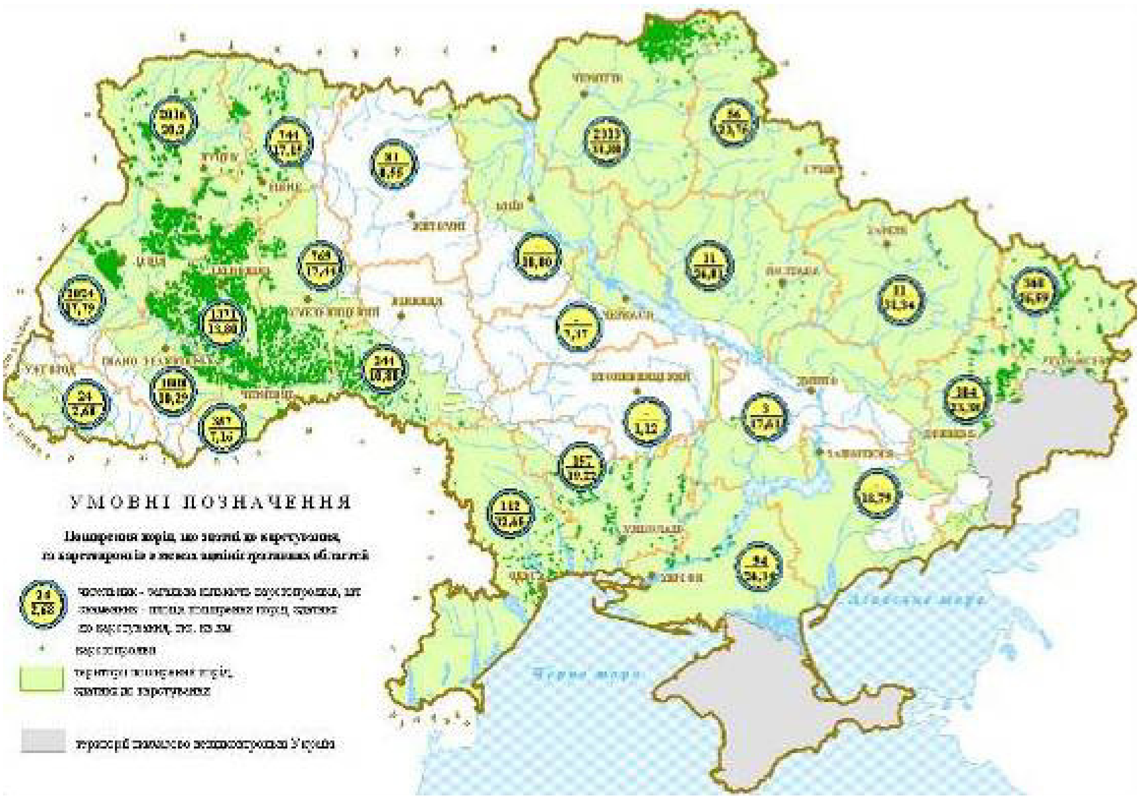


Figure 3 – Distributionof karsting rocks and of karsting within the administrative regions of Ukraine
(according to the State Service of Geology and Subsoil of Ukraine, http://www.geo.gov.ua)

Figure 4 – Distribution of loess soils within the administrative regions of Ukraine
(according to the State Service of Geology and Subsoil of Ukraine, http://www.geo.gov.ua)

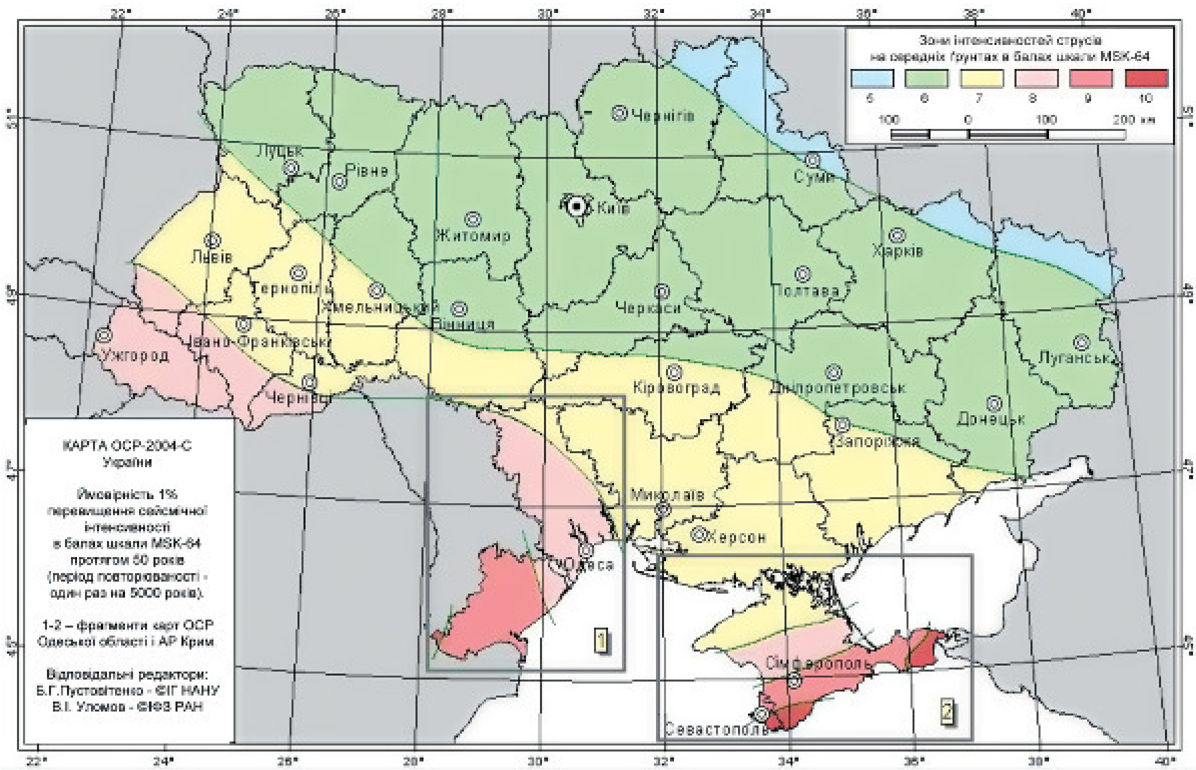


Figure 5 – Map of GSZ-2004-B general seismic zoning on the territory of Ukraine
(according to the data of SBC V.1.1-12: 2014) for high-risk facilities

In addition, modern technological requirements for tank battery lead to increase in the volumes of the TVS (tank vertical steel). At the same time, the pressure from the TVS, that is transmitted to the soil base, also significantly increases compared to the accumulated experience of these structures operation. Therefore, the cost of modern TVS construction in complicated engineering and geological conditions is increasing significantly.

It should be noted that according to [5] oil and oil product tanks are classified as high-risk objects (CC3 class of consequences). It, in turn, requires extremely high attention when designing and constructing these objects especially in difficult conditions. This situation requires development of qualitatively new geotechnical technologies that minimize the risks and ensure the safe operation of modern TVs, especially in difficult geotechnical conditions. Therefore, the improvement of design standards and the development of reliable methodologies for analysing such objects is definitely an urgent task.

Analysis of recent sources of research and publications. The studies of stress-strain state (SSS) of TVS are considered in papers [6], peculiarities of work under non-uniform deformations of foundations – [4], with seismic influences – [7]. In all these works, SSS of tanks is considered separately from the bases and foundations.

In papers [8 – 14] the results of changes investigations in the properties of soils during their soil-cement reinforcement, incl. dynamic. It should be noted that laboratory and field studies of deformation characteristics of soils, obtained mainly by specialists from Japan and the USA, determined that in conditions of significant seismic loading deformation characteristics of the soil become non-linear. Analysis of world and national experience in using different methods to reduce the dynamic and vibrational effects on weak, water-saturated, structurally unstable soils showed that the most effective means for their artificial transformation is cementation with the help of jet grouting or boring and mixing technologies [11 – 18]. Their main feature is that they enable to strengthenpractically the entire range of soils from gravel deposits to fine clays, mules, turfs. In this case, the destruction and simultaneous mixing of the soil with cement mortar in the mode of «mix-in-place» (mixing in place). Between the solid particles there are strong bonds due to binders, which greatly increase the strength of the soil and reduce its compressibility.

The effect of stabilization (strentghening, reinforcement) of the bases is that in a certain volume of weak soil a part of it is replaced by a rigid material – a soil cement, with a relatively large deformation module (E = 70 – 200 MPa). Natural soil, sandwiched between the created vertical soil-cement elements (SCE), also increases its mechanical parameters due to the impossibility of lateral protrusion.

Identification of general problem parts unsolved before. Today, the accumulated experience of operating the TVS in complex engineering-geological conditions on artificial grounds is still insufficient, especially when attak of such a dangerous geological phenomena as an earthquake. Therefore, the purpose of the work is to analyze the geotechnical decisions of the construction of the TVS on subsidence and weak soils in seismic areas, to develop an effective form of artificial earthquake-resistant foundations and to develop a method for its analysing, to estimate the probability of tank failure on artificial bases, to implement the development of design standards TVS.

Basic material and results. As a rule, tank subsidence occurs evenly, however, in difficult geotechnical conditions, the possibility of meeting design specifications during their operation due to non-uniform deformations of the foundation base is complicated.

Almost immediately after the hydraulic tests there is an non-uniform subsidence between the central part and the wall of the TVS due to different specific pressure on the soil of the wall weight and hydrostatic load. Pressure under the wall varies within 0.9 – 1.5 MPa, and under the central part of the bottom no more than 0.16 – 0.2 MPa. From the practice of the tank exploitation, there are cases when the difference of subsidence between the central and peripheral parts of the bottom reaches 0.6 – 0.8 m.

As it is known, non-uniform subsidence on the bottom area and on its perimeter cause additional deformations in the structural elements of the TVS, especially in the lower junction of the wall and the edges, and the additional stresses associated with them. The combination of operational stresses with additional from non-uniform subsidence can lead to the damage in the junction area or rupture of the bottom panel. Also, with a significant deformations of the cylindrical shell, possible damage in the junction of the stationary roof, wall and support ring, pontoon disfunction .

One of the effective methods of subsidence leveling in terms of the bottom area and its perimeter is the construction of an artificial base with interchangeable deformation characteristics. For the construction of this base is proposed a vertical reinforcement of soil-cement elements. The modulus of deformation of the created artificial base is considered weighted. Its value can be controlled by changing the distance between SCE.

Depending on the loads and engineering-geological conditions, determine the required number and length (up to 40 m) of SCE. A grid of SCE can be made with different steps without any interference or with their «intersection». Such an approach provides normative subsidence and trouble-free operation of the TVS in the most complicated engineering and geological conditions.

Another unresolved problem of normative documents is the earthquake resistance of TVSs, taking into account the improved soil properties.

For a better understanding of the problem of reducing seismic hazards, lets consider the main aspects of the theory of the seismic waves propagation in soil fields and seismic geotechnics. The transfer of wave energy from point to point occurs due to the elastic properties of the medium, therefore the stress wave is elastic. In the process of propagation of the wave, a part of its energy is lost, which leads to a decrease in the intensity of the dynamic load with a distance from its source and is called attenuation. The causes of the attenuation are different and are associated mainly with nonideal elasticity, discreteness and heterogeneity of any soils structure as a medium of propagation of elastic waves. By means of different mechanisms of energy loss, the following types of attenuation are distinguished: 1) the difference is caused by the decrease of the specific energy per unit of the wave area front in connection with its increase as the distance from the source; 2) dispersion in various heterogeneous media, which leads to a decrease in the energy of the wave in a particular direction; the dispersion of waves on any obstacle depends on its shape and size, as well as on the density and compressibility of the obstacles substance; 3) the absorption is due to the energy consumption of plastic and nonlinear-elastic deformation. Consequently, the presence of various obstacles and weak inhomogeneous soils in the path of a seismic wave leads to reflection and absorption of its energy that reduces seismic intensity.

The task of vibration analysis of the system «base – foundations – construction» is complicated by poorly predicted effects of resonant strengthening of seismic vibrations by loose near-surface soils: depending on the type and thickness of vibration layers of some frequency intervals can be selectively amplified, while others are almost completely absorbed. This phenomenon is due to the violation of the natural vibrations of the stratum near the free surface in the waves of this type. That is, the upper layers of the soil change the parameters of seismic waves, coming from the depths, and, thus, can change (both increase and decrease) the intensity of seismic vibrations depending on their dynamic properties. The level of ground water (water saturation) can produce an effect on seismic intensity in the case when water changes the physical and mechanical properties of soils, which should manifest itself in changing their elastic properties, in particular the velocity of transverse waves. Therefore, in order to design earthquake-resistant building is required not only information about the strength and location of possible earthquakes, but reliable data on forced vibrations of structures on certain soil substrates. To do this, certain characteristics of the soil, such as its dynamic compression and shear modulus, the damping factor, are determined, including the forecast of changes in soils properties during the operation of the structure, and depending on them, one of the possible models of basement soil behavior is taken for the analysis. One of the most important dynamic properties of soils is their seismic stiffness $V_s\rho$ (where V_s – the velocity of transverse waves propagation, ρ – soil density). At the same time, the higre $V_s\rho$ of the soil active layer is, the smaller the amplitude of its vibrations is.

In terms of dynamics, the thickness of the active layer is determined by the frequency characteristics ratio of the soil layer and the structure. At the same time, the most unfavorable in seismic terms is the case – the intersection of the frequency characteristics bandwidth of soil mass with its structure own oscillation frequencies. Thickness H of the soils that significantly effect the vibrations of earthquakes, is determined by the ratio $H=V_s/4f$ (where V_s – the average velocity of transverse waves in the soil layer; f – the value of the bandwidths intersection low frequency part of the soil layer frequency characteristics and the structure internal vibrations). If the frequency parameters of the soil layer and the internal vibrations of the structure do not overlap, there is a weak link between these processes. During seismic vibrations seismic waves occur. Longitudinal waves lead to compression and stretching of soil particles, while transverse waves cause tilt or lateral displacement. At a lateral displacement there is a danger of cohesive strength violation between particles of soil. Therefore, there is an additional problem – the ability of soils to change their mechanical properties when passing elastic waves through them. The essence of the effect lies in the fact that the soils consist of small and the smallest particles, in intervals (pores), between which there is water and gases. All resistance of such soil to external loading is carried out by means of a huge number of contacts between these particles, many of which are very weak. When the elastic wave passes, vibrations of soil particles with different velocities are excited, and the part of the contacts is broken. In addition, when a wave moves from a more dense to a loose soil layer and a substantial (twice or larger) increase in the amplitude of the vibration, adhesion failure becomes real. As a result, the strength of the soil significantly (sometimes several times) decreases. At the same time the soil becomes «liquid», this phenomenon is called «liquefaction» of the soil (it is in a state of suspended water). Water thus seeks to squeeze out, but this process requires some time, since it is limited to the permeability of the soil.

The most important task in analysing the vibrations of the system «base – foundation – structure» in all forms is the forecast of its resonance frequencies and peak displacement amplitudes, which are considered as the limiting (most unfavorable) conditions of the work of the structure. The fact is that in the spectrum of the seismic wave there are vibrations with frequencies close to the natural frequency of a number of structures (characteristic periods from 0.2 to 2 s). In the case of resonance, the stresses on the contact of the foundation with the soil sharply increase, as well as in the construction of the structure and the probability of destruction of this system increases.

The influence of the soil base on seismic fluctuations of the structure has a number of aspects: 1) through it the seismic effect on the structure is transferred (the structure, due to its massiveness and rigidity, has a reverse effect on the movement of the soil); 2) the base has its own mass and rigidity, which reduces the frequency of natural vibrations of the dynamic system «structure-base» (with increasing mass and stiffness of the soil the amplitude decreases and the frequency of vibration of the base increases); 3) during an earthquake, seismic waves are reflected from the foundation and dissipated in the basis.

The last two factors influence the size of the dynamic response of the structure, and therefore the seismic inertial loads that have an effect on on the structure.

The design of cylindrical TVS is a vertical, thin-walled cylinder, which is limited with the bottom and the roof. At the bottom of the reservoir lying on the base, there are relatively small stresses under pressure of the load from the liquid contained in it. In this case, the thickness of the bottom is 4 ... 12 mm and is mainly due to the conditions of the technology of assembly and welding works and corrosion resistance of the metal.

During the design of tanks in seismic areas with intensity higher than 6 points it is necessary to consider the additional requirements: 1) use of tanks with lower height; 2) in tanks with a floating roof or a pontoon to apply locks of soft type; 3) in case of usage the tanks with a stationary roof it is necessary to carry out calculation of the maximum height of filling of the tank with liquid to avoid hydrodynamic blow in a roof the wave arising in the tank from a horizontal push; 4) special devices (compensators) should be provided in the pipiline entry units with shut-off valves that ensure the strength and reliability of the mentioned unit.

The presence of liquid in the tank leads to a change in its own vibrations and forms of construction, the additional hydrodynamic pressure on the walls and bottom of the reservoir. In this case, for the thin-walled reservoirs, the hydrodynamic calculation is basic, since the mass of the liquid is much larger than the mass of the tank itself. The calculation determines the level of stresses in a tank wall and evaluates a surface wave height that arises during vibrations (to avoid spill from the tank and impact on the roof). For tanks with a floating roof or a pontoon one should consider horizontal inertial forces from a floating roof or a pontoon. That is, it is necessary to calculate various hydrostatic systems that simulate the tank for seismic influences, which are given by accelerograms. In general, reservoirs are expected to withstand the rollover and shifts from wind loads, non-uniform deformations of the foundations or seismic influences. At the next stage, the main and auxiliary structures of the tank are calculated. Tanks foundation is calculated for two groups of limit states: 1) ultimate limit state – on the bearing capacity for check of stability of tanks on overturning; 2) serviceability limit state – on deformations (absolute vertical settlements of the center and a contour circle of the foundation, differential settlements of ground taking into account local moistening of collapsible thickness, tilt).

In earthquakes conditions there is an addition to external vibrations – component of the seismic load from vertical soil vibrations, occurs further loads of the product on the wall and bottom of the tank (Fig. 6) – namely: 1) hydrostatic loads and loads of overpressure; 2) impulsive (inertial) component of hydrodynamic pressure; 3) convection (kinematic) component of hydrodynamic. The impulsive component of pressure arises from a part of the product moving in an earthquake together with a tank wall. Liquid sloshing in a tank create convective pressure and leads to emergence of waves on a product surface. Vertical vibrations of a tank base also induce additional load of its wall.

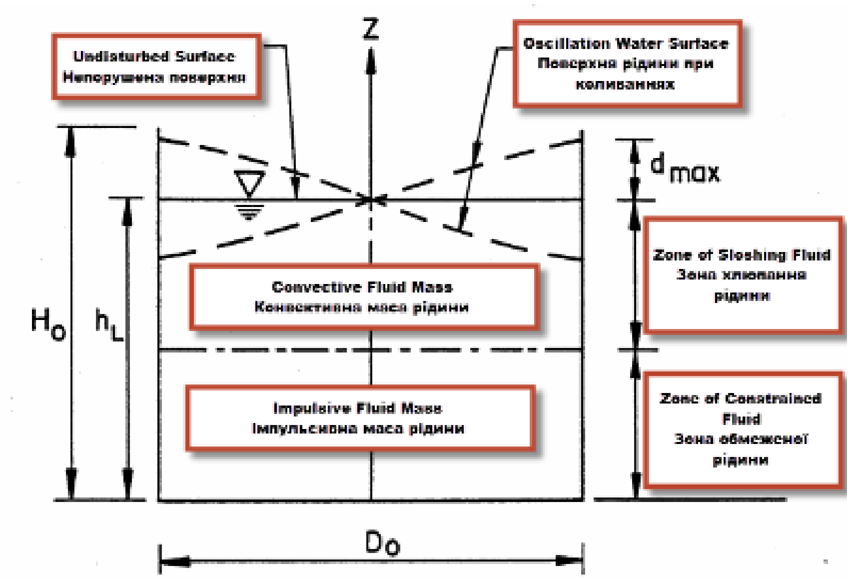


Figure 6 – The scheme of liquid sloshing in a cylindrical tank

Tank seismic resistance is considered to be provided if: a) the tank does not overturn during an earthquake (overturning criterion is the limit state at which on the external radius of the lifted part of the bottom a full plastic hinge appears); b) stability of the lower belt of a wall at action of longitudinal and cross loading is provided; c) durability condition for all bearing elements of the tank is provided. There are several concepts for reducing the seismic hazard by arranging pile foundations or improving the properties of soil bases by reinforcing them with vertical SCEs.

Concept number 1. Limitation of damage from liquefaction «limiting soil seismic shock absorber» (Fig. 7) is a seismic and extrusion technology to mitigate shocks during shocks during earthquakes, which includes a solid soil mass from the whole soil-cement wall. Such a structure can effectively limit the deposition and lateral displacement of the soil, as well as the displacement of structures.

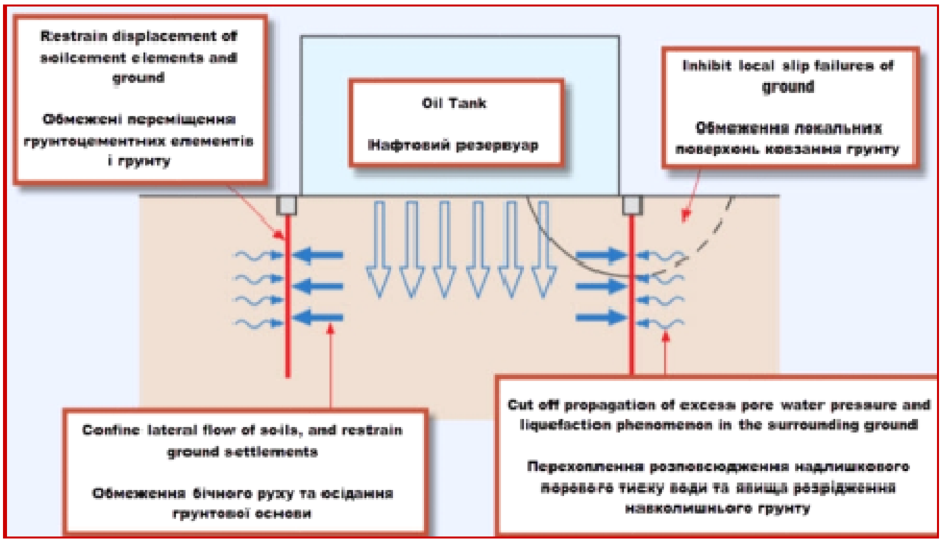


Figure 7 – Concept № 1 – Damage limitation from liquefaction «limiting soil seismic shock absorber»

Concept number№ 2. The method of limiting the lateral displacement of the soil due to its SCE reinforcement. Lateral displacement of the soils caused by their liquefaction during the earthquake and the horizontal displacement and subsidence of the tanks are reduced due to the SCE reinforcement of the ground in chessboard method from the existing containment bund, which protects the tanks with oil and petroleum products. Such technology further prevents the leakage of contaminated liquid from damaged pipelines.

Concept number № 3. Method of solid soil-cement lining. Soil liquefaction during an earthquake is limited by the use of a «limiting soil seismic shock absorber», resulting in the soil being in a closed solid cement wall. The leakage of contaminated liquid due to the displacement of the tank or damage to the pipeline is prevented by reducing both the values of foundations base subsidence of, and its unevenness.

Concept № 4. Method of SCE enclosing. The sedimentation and loss of stability of the oil-protective soil dam caused by earthquakes, as well as the leakage of contaminated liquid outside the dam, may be limited or prevented by the arrangement of the soil cement wall along the contour of the dam.

In addition, the soil liquefaction during an earthquake is limited by the use of a «limiting soil seismic shock absorber», through which the soil turns out to be a closed solid soil cement wall. This can prevent leakage of contaminated liquid due to displacement of the tank or damage to the pipeline.

*Concept number 5. Method of continuous artificial soil cement base (*Fig. 8). Reducing the influence of dynamic load on the aboveground part of the structure during the earthquakes due to the increase of elastic deformation parameters of the base.

Reducing the effect of the dynamic load on the aboveground part of the structure during the earthquakes can be achieved by reducing the acceleration and the vibration amplitude of the base of its foundations. One of the ways to reduce seismic intensity is to increase seismic impedance $V_s\rho$ of the active layer of soil by increasing the velocity of propagation of seismic waves in it. Such an effect can be achieved by increasing the elastic deformation characteristics of the base, using the boring and mixing technology [11, 15].

With this approach it is possible to increase the modulus of elasticity of the base to 500 – 2000 MPa, the rate of propagation of waves up to 600 – 1000 m/s at constant density.

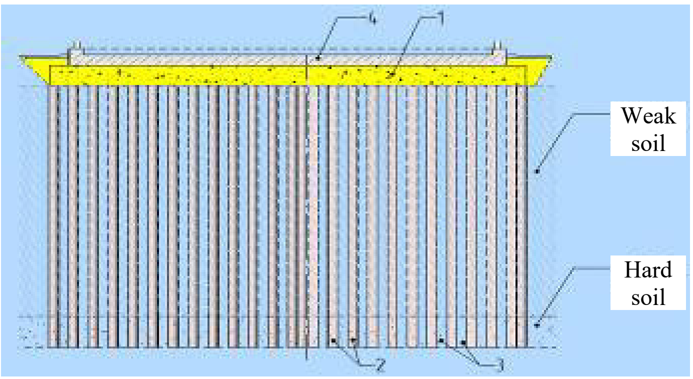
Improvement of the damping characteristics of an artificial base occurs due to the presence of a gravel or sand pillow, as well as due to the presence of friction and adhesion of sandwitched soil on the surface of the SCE contacts. Therefore, the vertical components of the seismic impulse (vertically directed tremors) the pillow damps and only in a weakened form, transfers to the base slab. In the zone of artificial base, vertical SEEs partially absorb and dissipate the energy of a seismic wave (dissipation) in a manner similar to a pile foundation. The elimination of thixotropic properties and properties of soil liquefaction occurs due to local cementation within the SCEs and the increase in the resistance of the soil shift between these elements. It also increases the resistance of the filtration consolidation of the weak base due to its reinforcement. The main idea of the authors is the development of a universal artificial base, which will provide regulatory and technological requirements for both the static conditions of TVS exploitation on subsidence and weak soils, as well as in the case of seismic influences of varying intensity. As an example, geotechnical solutions for the oil tank are given TVSI-20000 of oil pumping station «Avgustivka» (Avgustivka village, Biliaivka district, Odessa region).

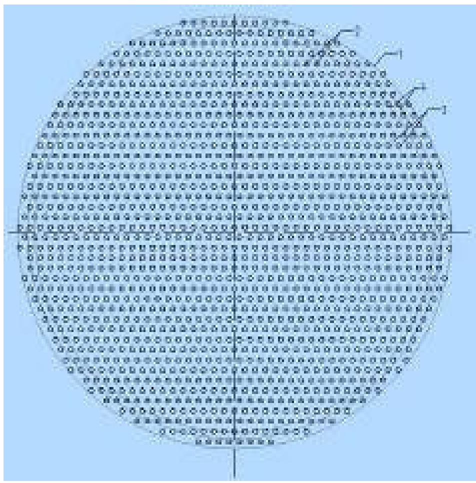
Technological parameters of TVS-20000 presented in the Tab. 1.

Geometric parameters TVS-20000:
1) nominal volume 20000 m^3;
2) geometric volume 20956 m^3;
3) height of the wall 17.926 m;
4) inner diameter 39.9 m;
5) area of the product mirror 1250.4 m^2.

The diameter of the base slab is approximately 40.5 m. Pressure under the bottom of the base slab at hydro testing is 168.14 kPa, at operation – 180.86 kPa. The uniformly distributed load along the contour of the foundation during testing is 31.65 kN/r.m., at operation – 40.33 kN/r.m., at wind loads – ±6 kN/r.m., at seismic influences – +353,73/-268.67 kN/r.m. The magnitude of the equilibrium of horizontal seismic forces transferred from the construction of the tank to the base slab was 65.500 kN.

The weak soil of the base in the case of earthquake action can go into a liquid state (to obtain a thixotropic properties), to obtain an additional compacting, resulting in excessive deformations of the tank. The complexity of the second site is characterized by the presence of a subsidence thickness of more than 5 m. The estimated seismic intensity of the plot is 9 points.





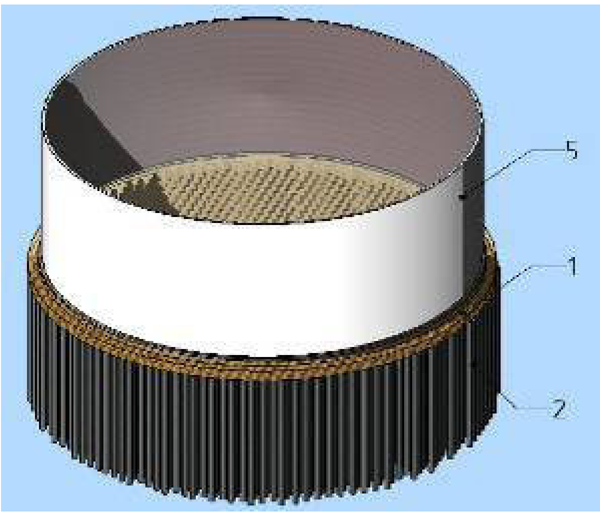


Figure 8 – Dynamically stable soil cement base:
a – section of dynamically stable soil cement base;
b – plan of the reinforced base;
c – spatial view of the structure on a reinforced base;
1 – sand or gravel-pebble pillow;
2 – vertical soil cement elements;
3 – natural soil, sandwitched between vertical soil cement elements;
4 – foundation slab;
5 – aboveground structure

Table 1 – Technological parameters of oil storage tank TVSI-20000

Parameters	Value
Product density (oil), t/m^3	0.89
Expected level of product filling, m	16.2
Water level at hydrotest, m	16.75
Internal overpressure	missing
Standard internal vacuum	missing
Operation rate (cycles per year), min/max	20/100
Characteristic value of snow load, kg/m^2	102
Characteristic value of wind load, kg/m^2	51
Seismic intensity, points	8
The temperature of the coldest days with the use factor of 0,98, ^{0}C	- 24
Maximum temperature of oil storage, ^{0}C	+ 25
Design service life, years	40
Design wave altitude of oil at seismic loadings, m	0.32
The size of an allowance for corrosion for sheets of a wall, mm	0
Minimum marking of surface edge in regard to the surface of the crust, mm	+0.5

At these conditions, several geotechnical decisions were considered:

1) cutting of the soil weak and subsidence mass with reinforced concrete piles in the section 350x350 mm for their resistance to strong soils, as well as the elimination of the sedimentary properties of the soil of the inter-piles space by deep compaction (intallation of soil piles in diameter of 300 mm), errection of the foundation wall of 0.7 m thick over the piles, a swing joint of piles with a slab;

2) the same as in the first variant, but on top of the piles is assumed that the gravel pillow is arranged in order to damper the fluctuations of the reservoir and avoid the transfer of horizontal loads to the piles;

3) arrangement of the artificial foundation by reinforcing the weak and subsidence soil with vertical SCE with a diameter of 500 ... 650 mm, then the same as in the second variant.

The perception of horizontal seismic loading due to the work of piles on the soil is provided only with a significant amount (~ 1000 pcs.), Which is economically inexpedient, since the vertical load on the piles will not be more than 35% of the permissible. Therefore, this option was not further compared.

The variant with vertical SCE was much cheaper and could be realized over a shorter period of time.The length, the diameter and the step of SCEs were determined by the iterative method. The main criterion for calculating was the providing of less than the critical values of center subsidence and the extreme calculation points of the base slab, the tank tilt, as well as the load bearing capacity of the underlying seismic influences. As a result of calculations it was established that the optimal diameter of SCE is 500 mm, step – 1,0 m (2d).

Table 2 shows comparison of two variants of the foundations.

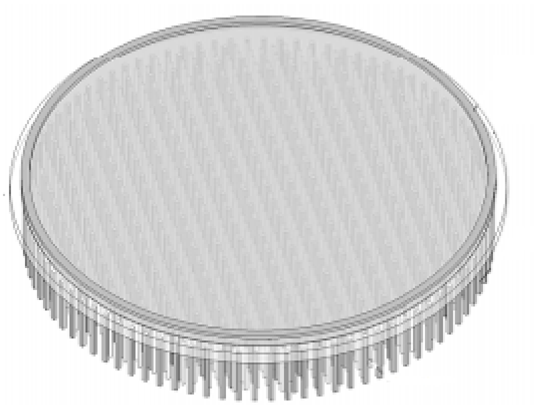
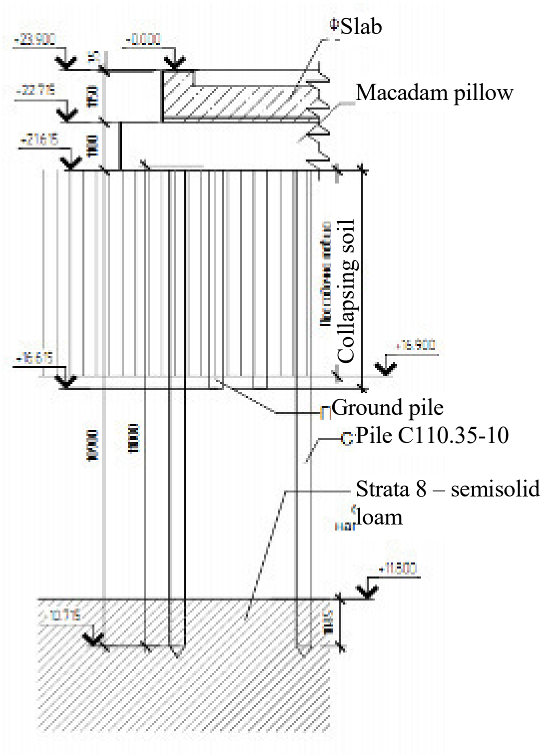
From the Table 2 is evident that variant with the use of the artificial base, by reinforcing the weak and subsidence soil with vertical SCEs for one of the TVS-20000, an economic effect of more than 2.7 million hryvnas was achieved and allows to shorten the construction period to 38 days.

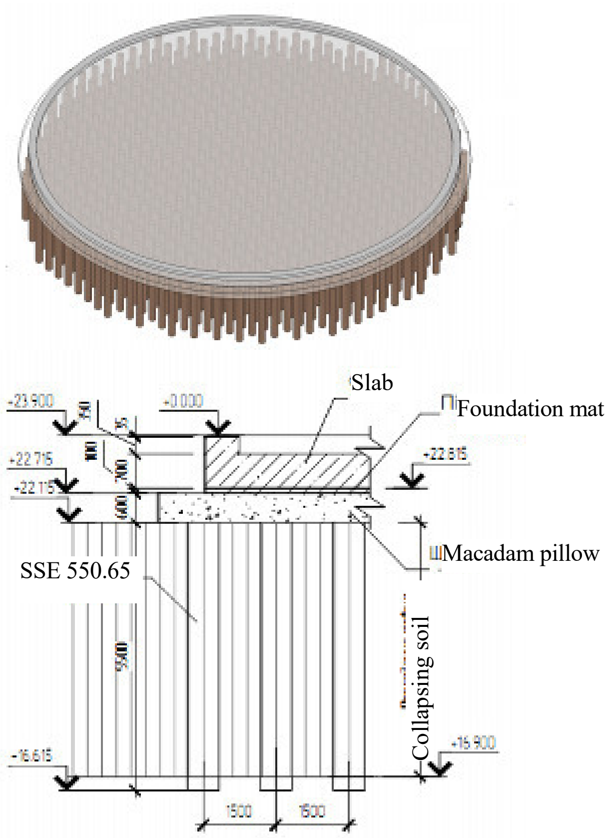
The authors also performed the probabilistic calculation of the system «artificial base – foundations – tank». Distribution and statistical parameters of the RV (random value) of the TVS foundation slab tilt are shown in Fig. 9 (the value of the tilt is multiplied by 10^{-4}). With subsequent loading of the tankss, the absolute subsidence of the base increases and is clearly fading. At the same time, the probability of failure on the criterion of subsidence does not exceed 0.001, and according to the criterion of the tilt – 0.07.

On the basis of statistical data simulation of the reinforced base subsidence and foundation slab tilt, the probability of construction failure and faultless operation according to the criteria of absolute settling (Fig. 10) and the tilt is determined, depending on the percentage of SCR weak base reinforcement. By simulation, it was found that the probability of failure on the criterion of a tiltl depending on the percentage of reinforcement (15 ... 25%) of SCE weak base ranged from 0.03 to 0.05.

The probability of failure of the construction according to the criterion of the maximum allowable foundation slab weight is less than 0.01. Based on the results of simulation for the reliability level p = 0.9, the minimum required percentage of reinforcement of the base is selected VSCE (i = 19%). This task has shown that with the help of a probabilistic approach, the necessary percentage of weak base reinforcement is substantiated to ensure the failure-free operation of the structure during its exploitation.

Table 2 – Techno-economic comparison of foundations TVS-20000

<table>
<tr><th>№</th><th>Name and scheme of the foundation variant</th><th>Performance time</th><th>Cost of work and materials</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td rowspan="10">1</td><td rowspan="10">Cutting of the subsidence thicket of the soil by reinforced concrete piles and their reliance on strong soils, elimination of the collapsing properties of the soil of the inter-tidal space by deep seals
(the arrangement of ground piles)


</td><td colspan="2">1. Reinforced precast-concrete piles of length 11 m and of section 350x350 mm – 374 piles.</td></tr>
<tr><td>32 calendar day</td><td>Without delivery – 2 079 000 UAH.
Work –
1 247 400 UAH.</td></tr>
<tr><td colspan="2">2. Ground piles of diameter 300 mm and of length 5 m – 917 piles.</td></tr>
<tr><td>45 calendar day</td><td>450 000 UAH</td></tr>
<tr><td colspan="2">3. Macadam pillow H = 1100 mm.</td></tr>
<tr><td>11 calendar day</td><td>176 000 UAH</td></tr>
<tr><td colspan="2">4. In-situ concrete slab.</td></tr>
<tr><td>11 calendar day</td><td>3 200 000 UAH</td></tr>
<tr><td>**Total –
128 calendar day**</td><td>**Total cost –
7 152 400 UAH**</td></tr>
<tr><td></td><td></td></tr>
</table>

1	2	3	4
2	Arrangement of the artificial bases by reinforcing the collapsing soil with soil-cement elements 	1. Soil-cement elements of diameter 650 mm and of length 5.5 m – 616 piles.	
		40 calendar day	1 124 230 UAH
		2. Macadam pillow H = 600 mm.	
		10 calendar day	96 000 UAH
		3. In-situ concrete slab.	
		40 calendar day	3 200 000 UAH
		Total – 90 calendar day	**Total cost – 4 420 230 UAH**
	Economic effect	**38 calendar day**	**2 732 170 UAH**

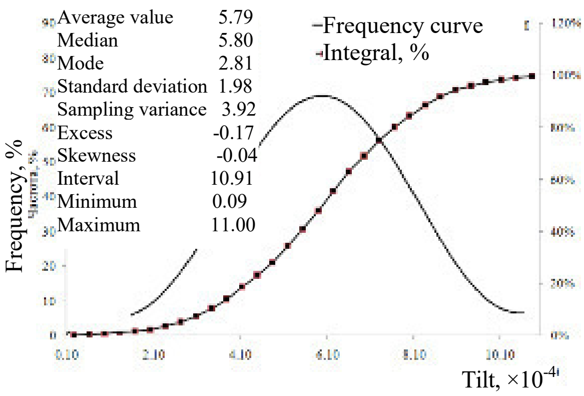


Figure 9 – Distribution of tilt RV of tank foundation slab on the results of the simulation of the MCE (the value of the tilt is multiplied by 10^{-4})

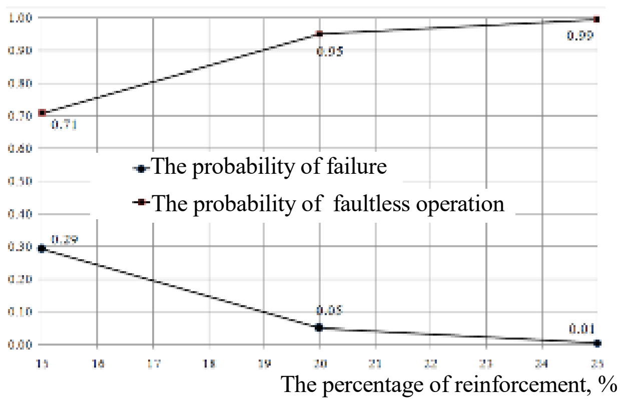


Figure 10 – The probability of failure and failure-free operation of the structure on the criterion of absolute settling, depending on the percentage of the base reinforcement

As a result, it is possible to draw the following **conclusions:**

1. Normative documents for the design of TVS should be supplemented with modern methods of the system «base – foundations – tank» analysis, technologies for vertical reinforcement of soils with specific properties, etc.

2. With consistent calculation of the soil base, foundations and tank, it is possible to consider more accurately the SDS of the entire system. The probability of design failure according to the criterion of the tilt and absolute deformation is satisfied with the percentage of reinforcement in the range of 15 ... 20 %.

3. In the arrangement of artificial foundation, the method of SCE vertical reinforcement is the ability to regulate the deformability of the base and in accordance with the alignment of subsidence of the central part of the bottom and points along the contour of the tilt in accordance with actual stresses and engineering-geological properties.

4. The variant of the foundation slab on an artificial soil cement base, which transforms the weak and subsidence thickness into a composite material, is earth-resistant, worth less than a pile and is more technologically efficient. All the technological and regulatory requirements for the exploitation of tanks are met.

5. Due to the reinforcement of a part of the weak and subsidence base soil mass, the amplitude of the vibrations of the reservoir decreases, the nature of the acceleration of the soil changes, and the values of soil acceleration in the pit bottom level drop. This result is ensured by increase in the velocity of seismic waves spread in an artificial soil cement base, as well as by increasing the strength and deformability characteristics.

6. At seismic influences with intensity of 9 points the maximum horizontal displacement of the tank top didn't exceed 6 mm, a bottom – 10 mm. The difference of bottom concerning top displacement is 16 mm that less than 20 mm. The tank does not overturn; shear strength of foundation relatively of crushed-stone pillow is achieved.

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